CAN MASSIVE STARS BE FORMED BY ACCRETION?

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ABSTRACT. Although massive stars play a critical role in the production of turbulent energy in the ISM, in the formation and destruction of molecular clouds, and ultimately in the dynamical and chemodynamical evolution of galaxies, our understanding of the sequence of events which leads to their formation is still rather limited. Because of their high luminosities we can expect radiative acceleration to contribute significantly to the evolution. Thus, we cannot simply "scale up" theories of low mass star formation. Furthermore, OB stars form in clusters and associations; their mutual interactions via gravitational torques, powerful winds and ionizing radiation contribute further to the complexity of the problem.

We show that massive star formation requires extensive grain preprocessing and an accretion disk in order to reduce the effects of radiative acceleration. Even though no massive disk has yet been observed around a main sequence massive star, such disks should be the natural consequence of the star formation process even in the high mass case. The detailed structure and evolutionary history of massive circumstellar disks has important consequences with regard to the early evolution of these protostars. Disks provide a reservoir of material with specific angular momentum too large to be directly accreted by the central object. Only after angular momentum is transported outwards can this material contribute to the final mass of the star. The transition region disk-star will strongly influence the star's photospheric appearance and how the star interacts with the disk. The relative high densities in these disks provide the environment for the further growth and evolution of dust grains, affecting the disk's opacity and consequently its energetics and appearance. The disk can be expected to interact with stellar outflows and is likely to be directly responsible for the outflows associated with star formation.

The above processes, in particular the photoionization of the disk by hard stellar photons and disk-stellar wind interactions can explain the existence of UCHIIs and the inferred short lifetimes ($t \sim 10^5$ yr) of massive disks around massive stars.

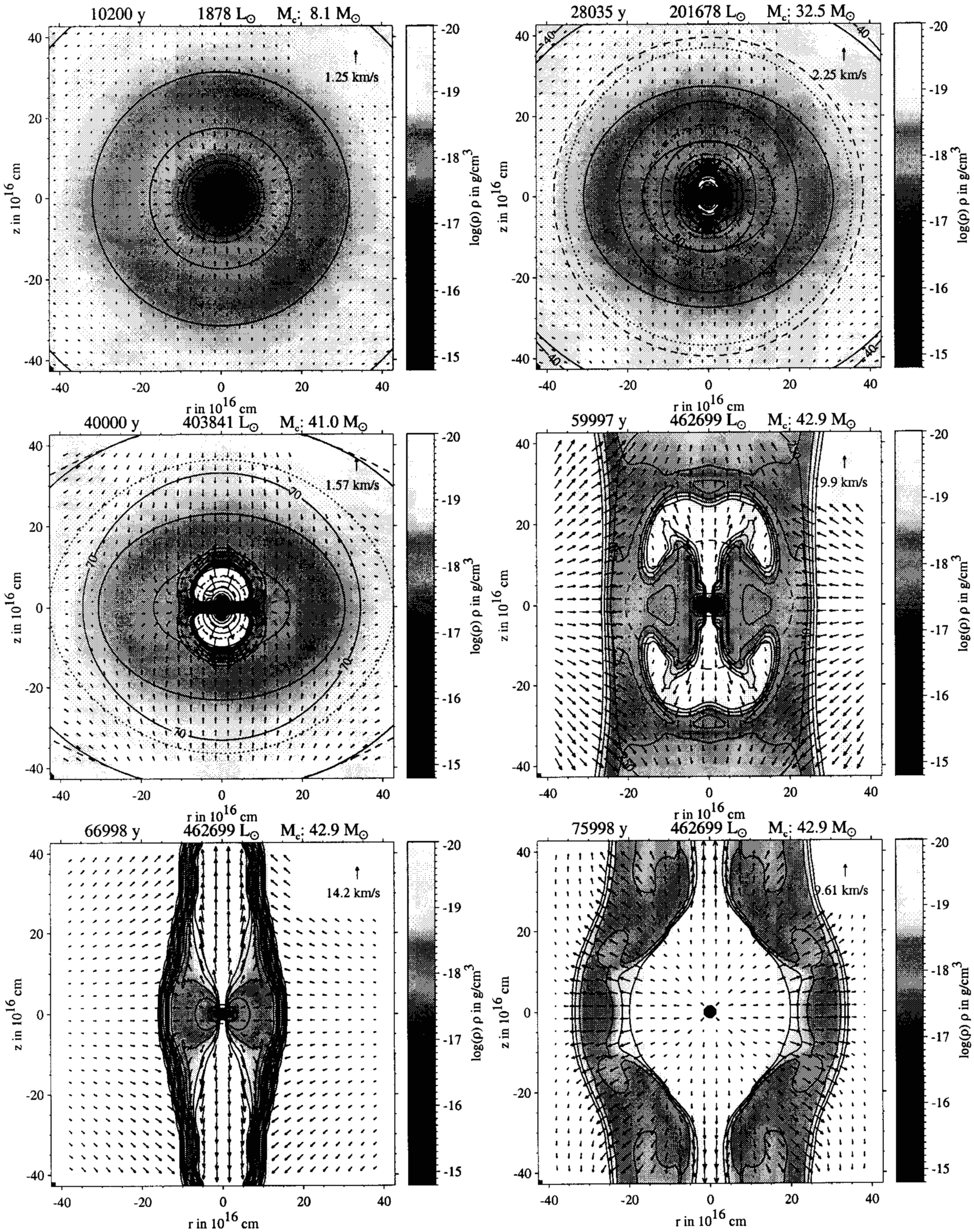

Figure 1: Density and velocity evolution of a slowly rotating 120 $M_\odot$ cloud.

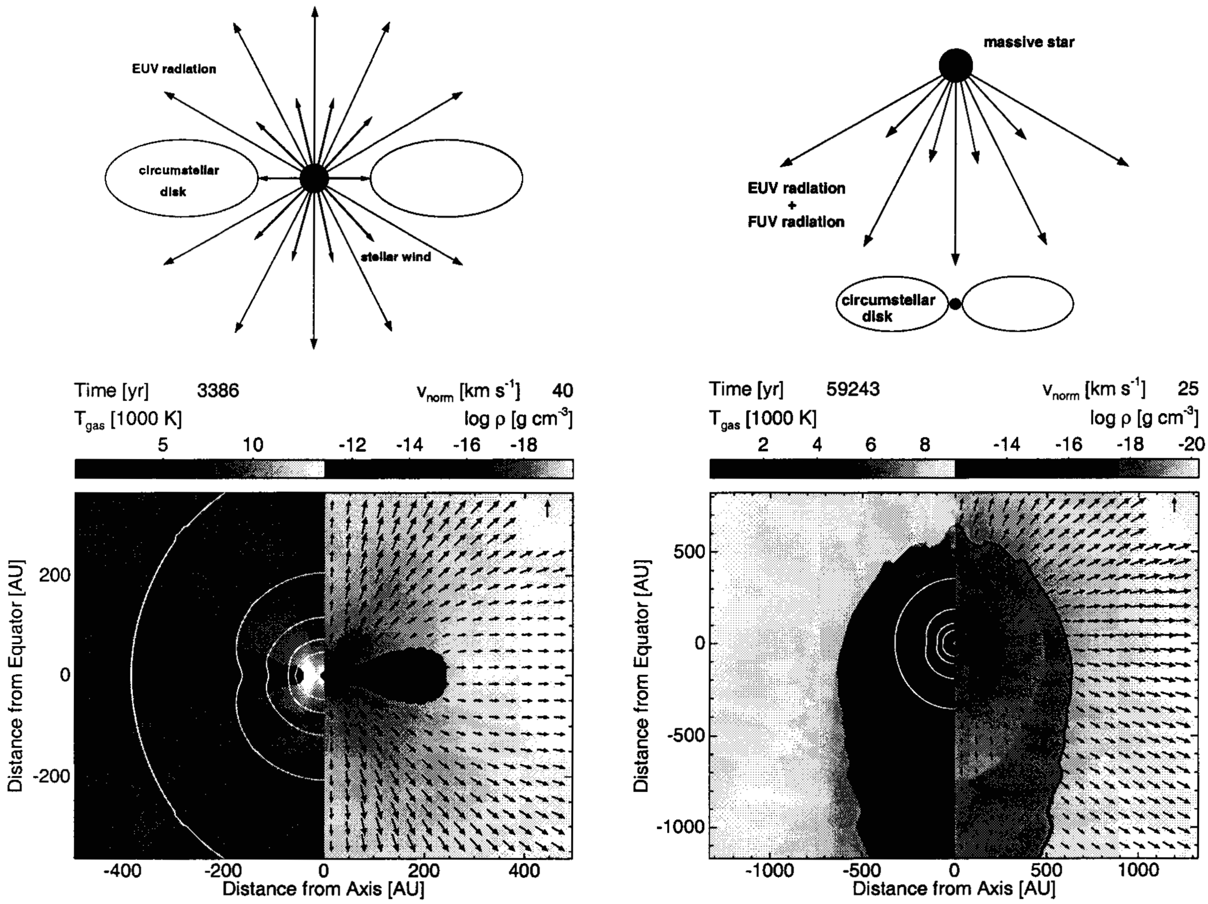

Figure 2: Quasi-steady state density, temperature, and velocity structure of a disk and its surroundings illuminated by EUV photons from the central massive star (*left*). and of an evolving low-mass system illuminated by EUV and FUV photons from a nearby massive star (*right*).

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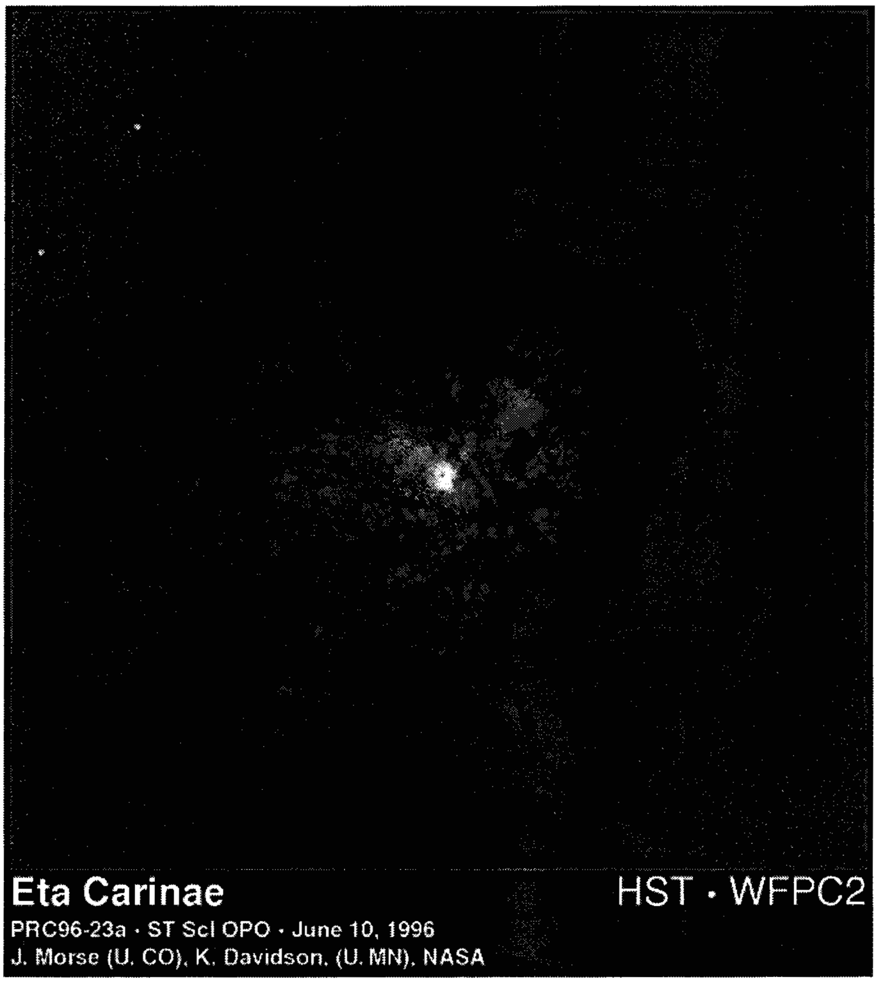
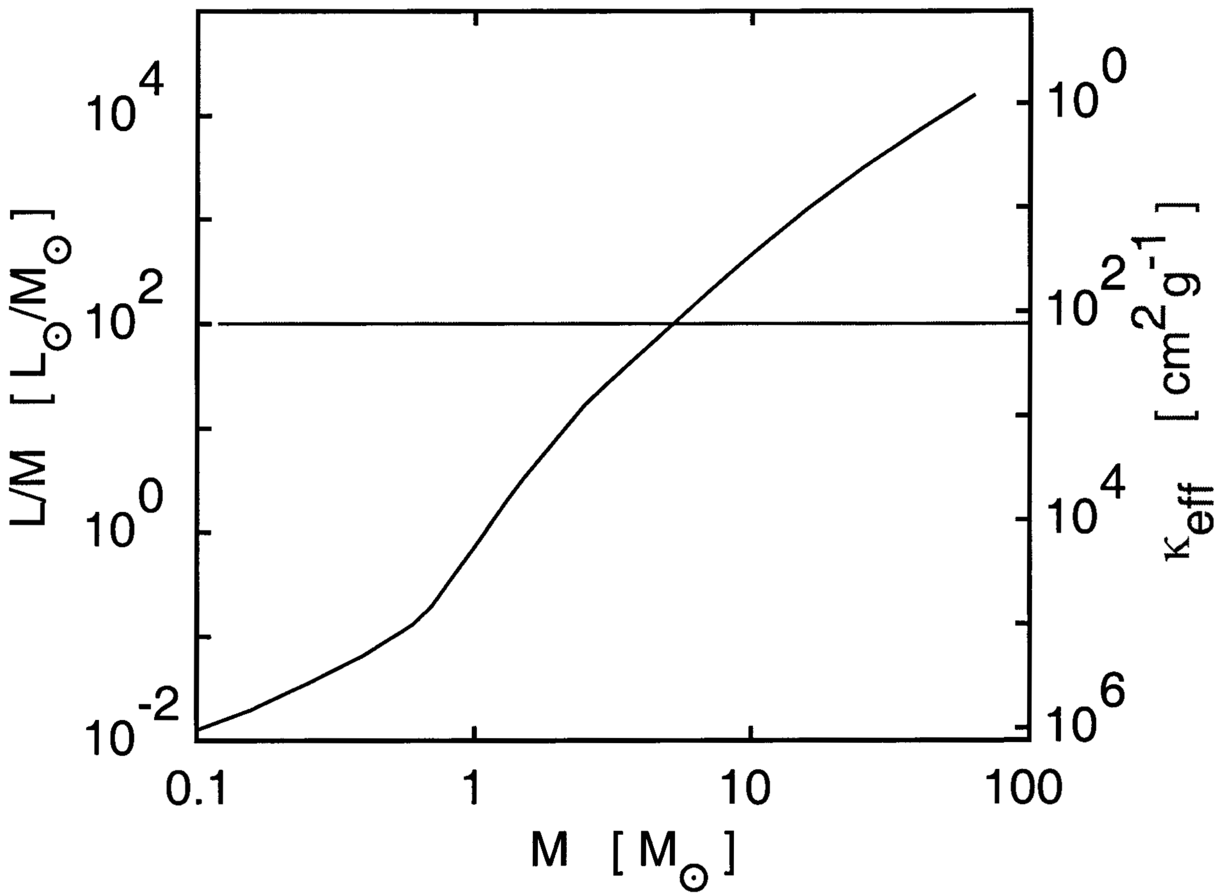


Accretion can occur if the acceleration due to gravity exceeds the radiative acceleration of the embryo source

$$\frac{GM}{r^2} > \frac{\kappa_{\rm eff} L}{4\pi r^2\, c}, \qquad \text{where} \qquad L = L_* + L_{\rm acc}$$

which translates into

$$\kappa_{\rm eff} < 130\ {\rm cm^2\,g^{-1}} \left[\frac{M}{10\ {\rm M_\odot}}\right] \left[\frac{L}{1000\ {\rm L_\odot}}\right]^{-1}$$



- Kahn (1974): Spherical symmetry (1D), steady-state infall
  $\rightarrow$ radiative reprocessing reduces $\kappa_{\rm eff}$
- Yorke & Krügel (1977): 1D, oscillatory accretion
  $\rightarrow M_*/{\rm M_\odot} = 3\,(M_{\rm cloud}/{\rm M_\odot})^{1/2}$ (Yorke 1979)
- Wolfire & Cassinelli (1987): 1D, steady-state infall
  $\rightarrow$ destruction of $0.05 - .25\ \mu$m grains necessary

HOW CAN YOU FORM MASSIVE OBJECTS?

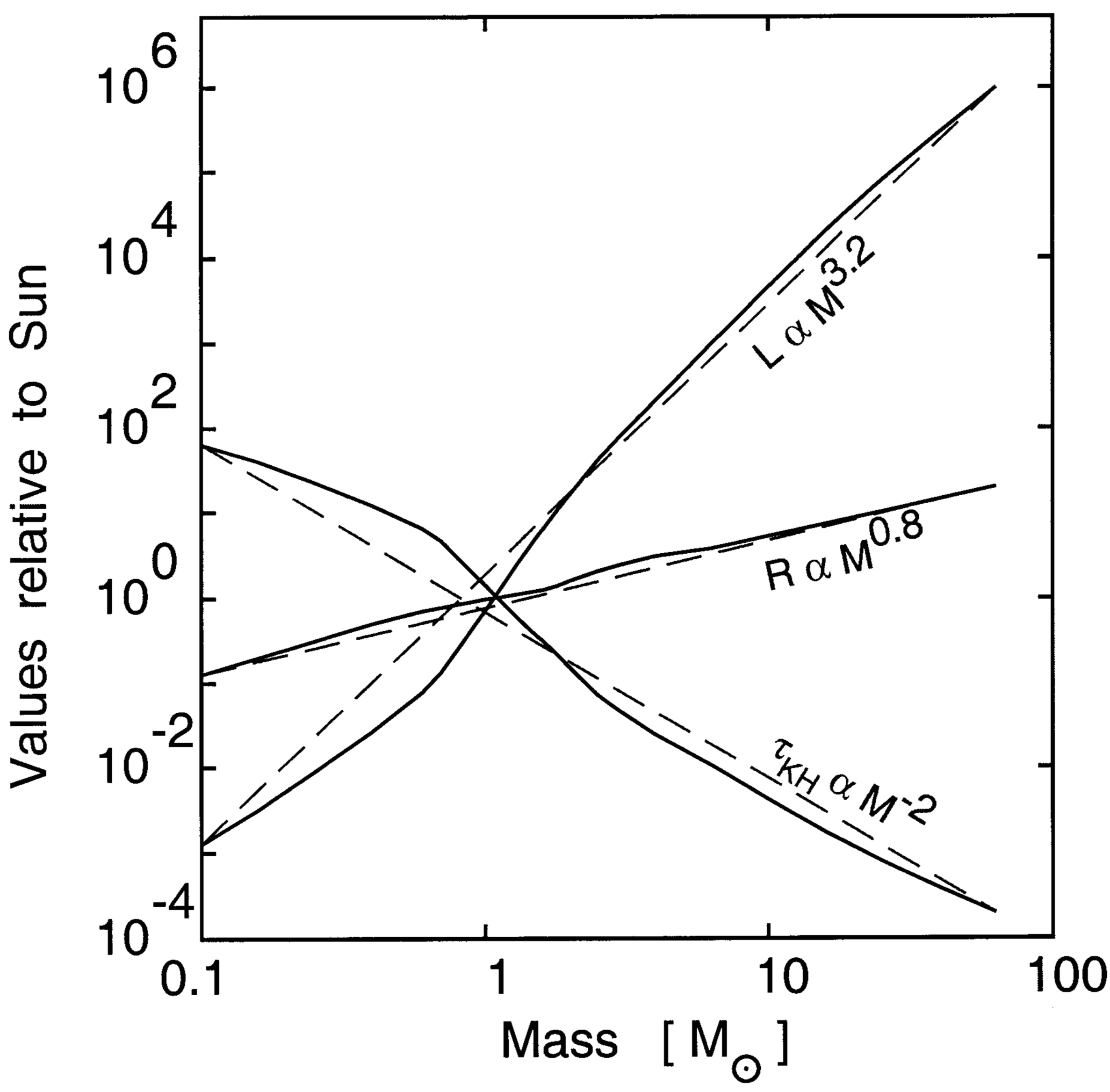
- Reduce $\kappa_{\rm eff}$
  - Modify absorbing and scattering material
  - Accrete optically thick "blobs" of material

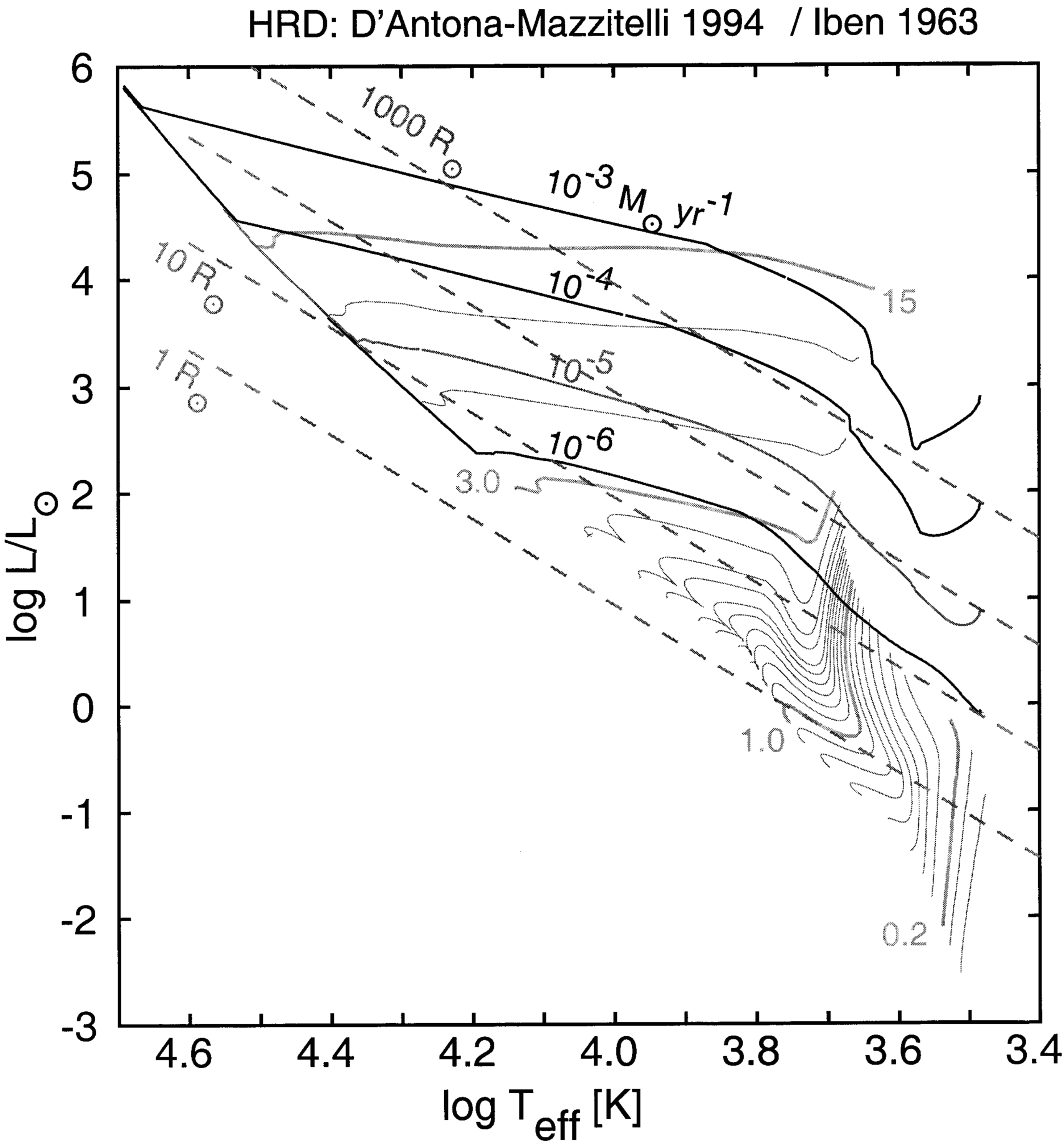
$$\kappa_{\rm eff} = \frac{\pi R_{\rm blob}^2}{M_{\rm blob}}$$

- Reduce L
  - Disk "beaming" effect
  - Accrete during quiescent phases
- Increase Gravity
  - Force material onto star by sheer weight
  - Form massive stars within a dense cluster of not so brightly radiating objects

$$\rho_{\rm objects} \gg \rho_{\rm gas}$$

Luminosity and Radius versus Mass
for main sequence stars




HRD: D'Antona-Mazzitelli 1994 / Iben 1963
1000 $R_\odot$
10 $R_\odot$
1 $R_\odot$
10^{-3} $M_\odot$ yr^{-1}
10^{-4}
10^{-5}
10^{-6}
15
3.0
1.0
0.2
log $L/L_\odot$
log T_{eff} [K]
6
5
4
3
2
1
0
-1
-2
-3
4.6
4.4
4.2
4.0
3.8
3.6
3.4

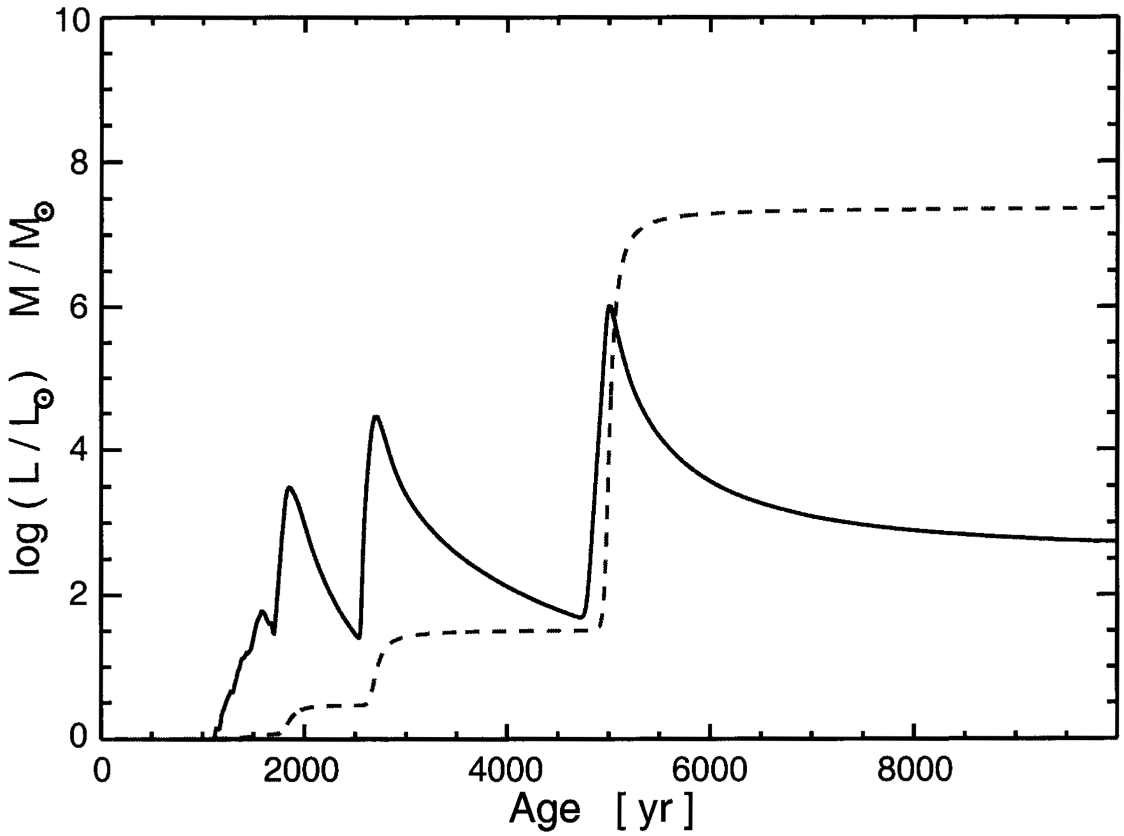
SPHERICALLY SYMMETRIC COLLAPSE

Suttner, Yorke, Lin (1999, ApJ, 524, 857)

CHARACTERISTICS OF THE CASES CONSIDERED

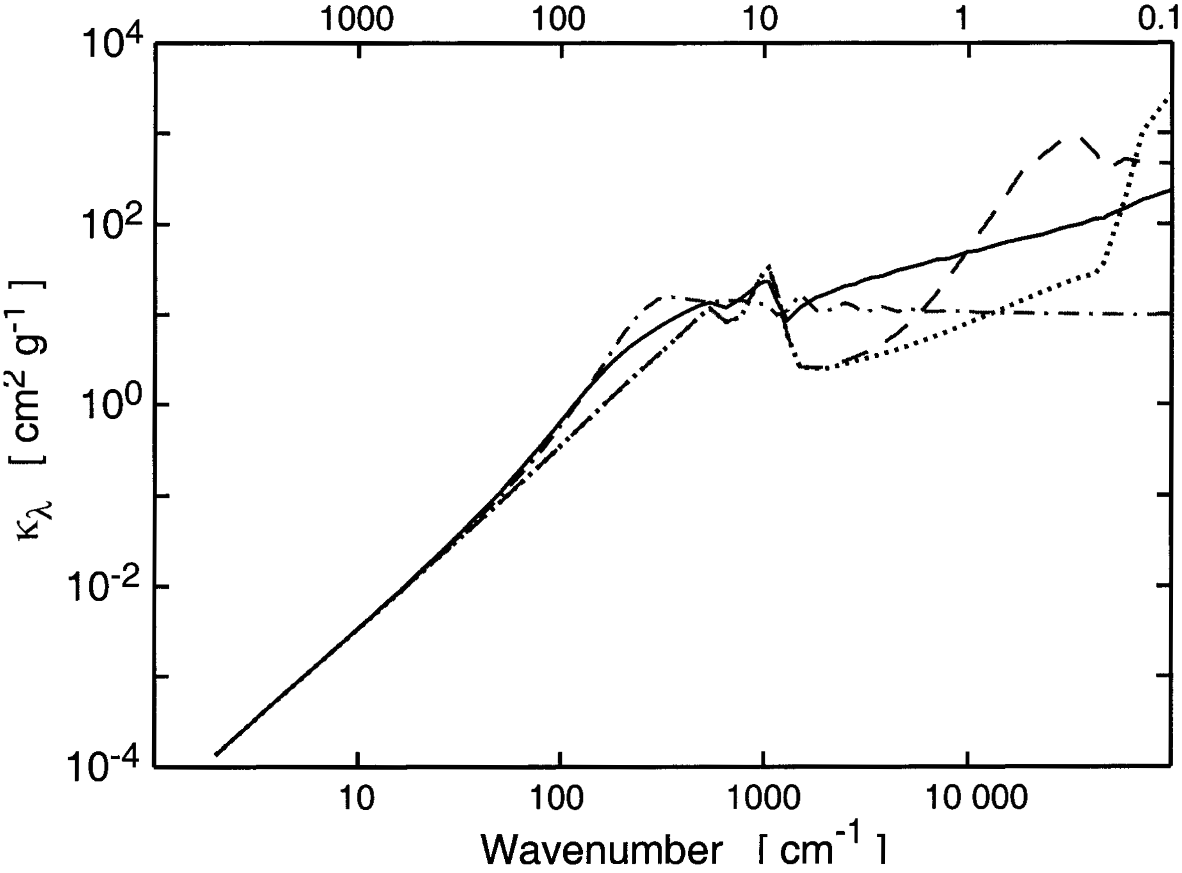
model	M_{tot} ($M_\odot$)	t_{ff} (10^3 yr)	t_{evol} (10^3 yr)	M_* ($M_\odot$)
3MS	3	5.0	58	3.0
C_3MS	3	5.0	32	3.0
5MS	5	3.9	48	4.4
C_5MS	5	3.9	45	4.9
8MS	8	3.1	56	6.8
C_8MS	8	3.1	61	7.8
10MS	10	2.7	55	6.6
C_10MS	10	2.7	68	6.5
C_10MS_i	10	2.7	67	7.2
C_10MS_i10	10	2.7	67	7.4

NOTE.— M_{tot} = beginning clump mass; t_{ff} = initial free-fall time scale; t_{evol} = total time calculated; M_* = final mass of central core. Models denoted by "C_" include the effects of coagulation, cratering, and shattering.



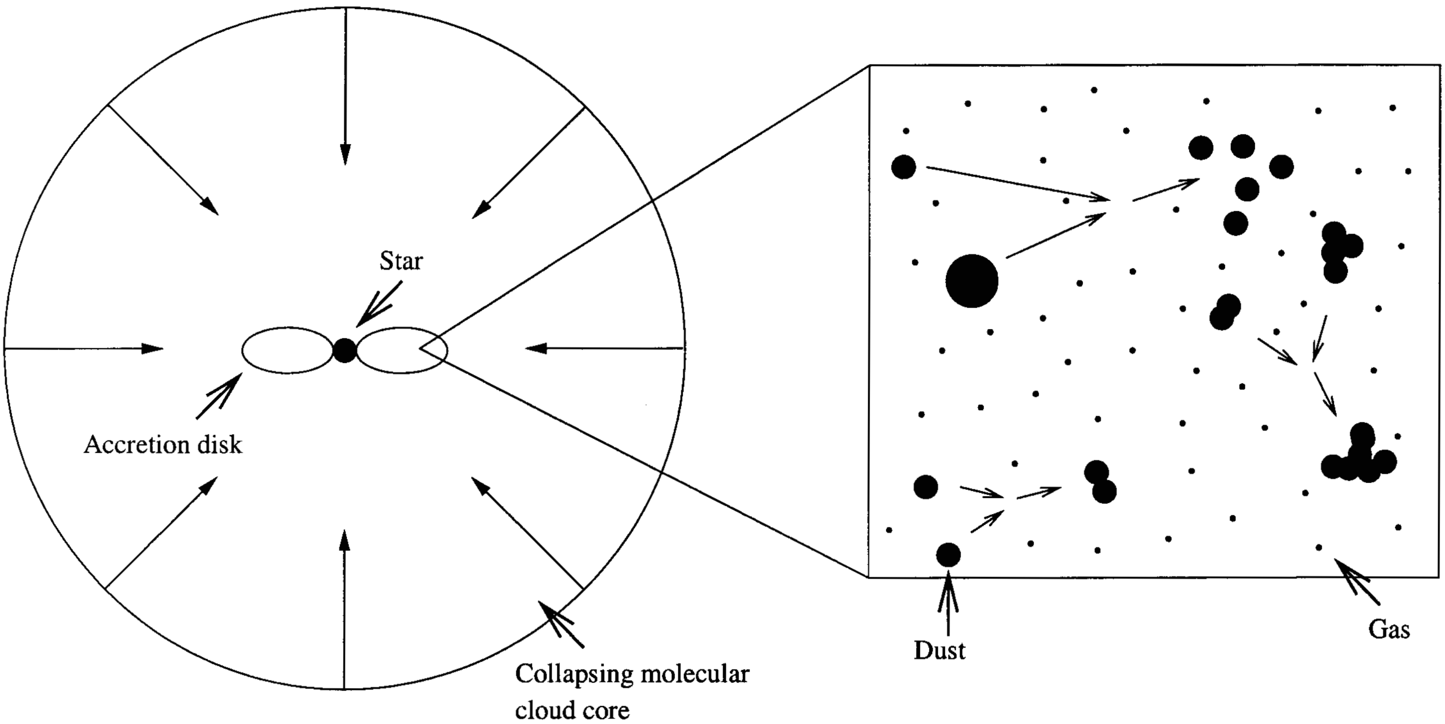
Evolution of core luminosity L and core mass M of model C_10MS_i10.

GRAIN OPACITIES

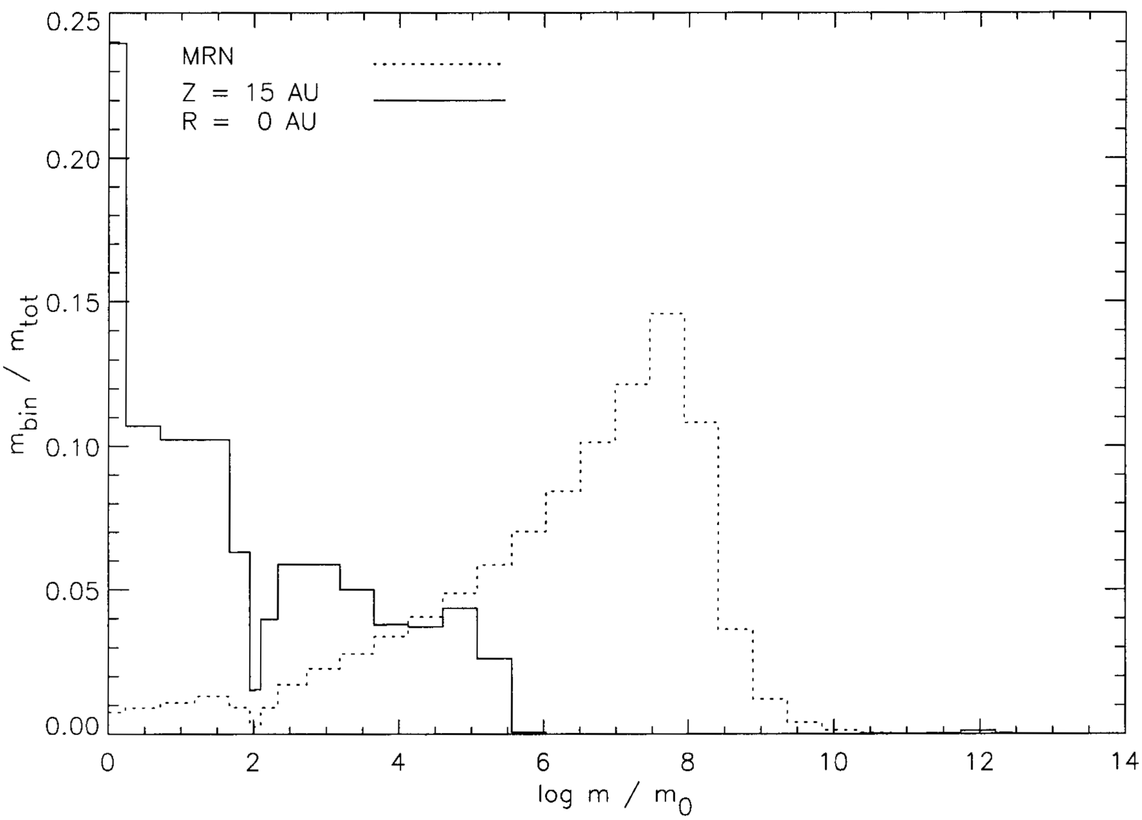


Specific extinction coefficients of dusty gas under the assumption that a) all grains have $a = 5$ nm; b) all grains have $a = 0.1\ \mu$m; c) all grains have $a = 5\ \mu$m; d) MRN distribution

Dust Evolution in Protostellar Disks

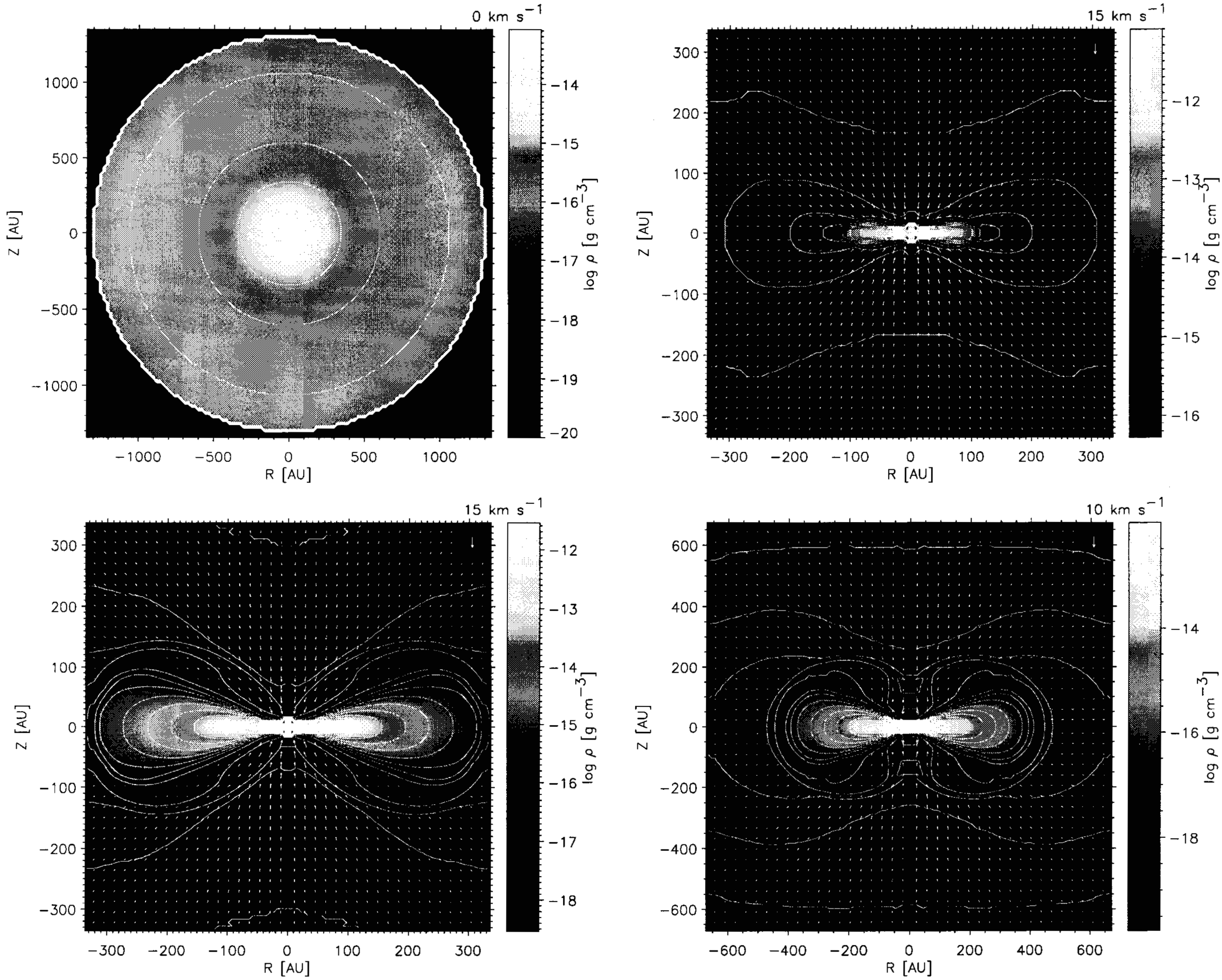


Schematic representation of coagulation and shattering



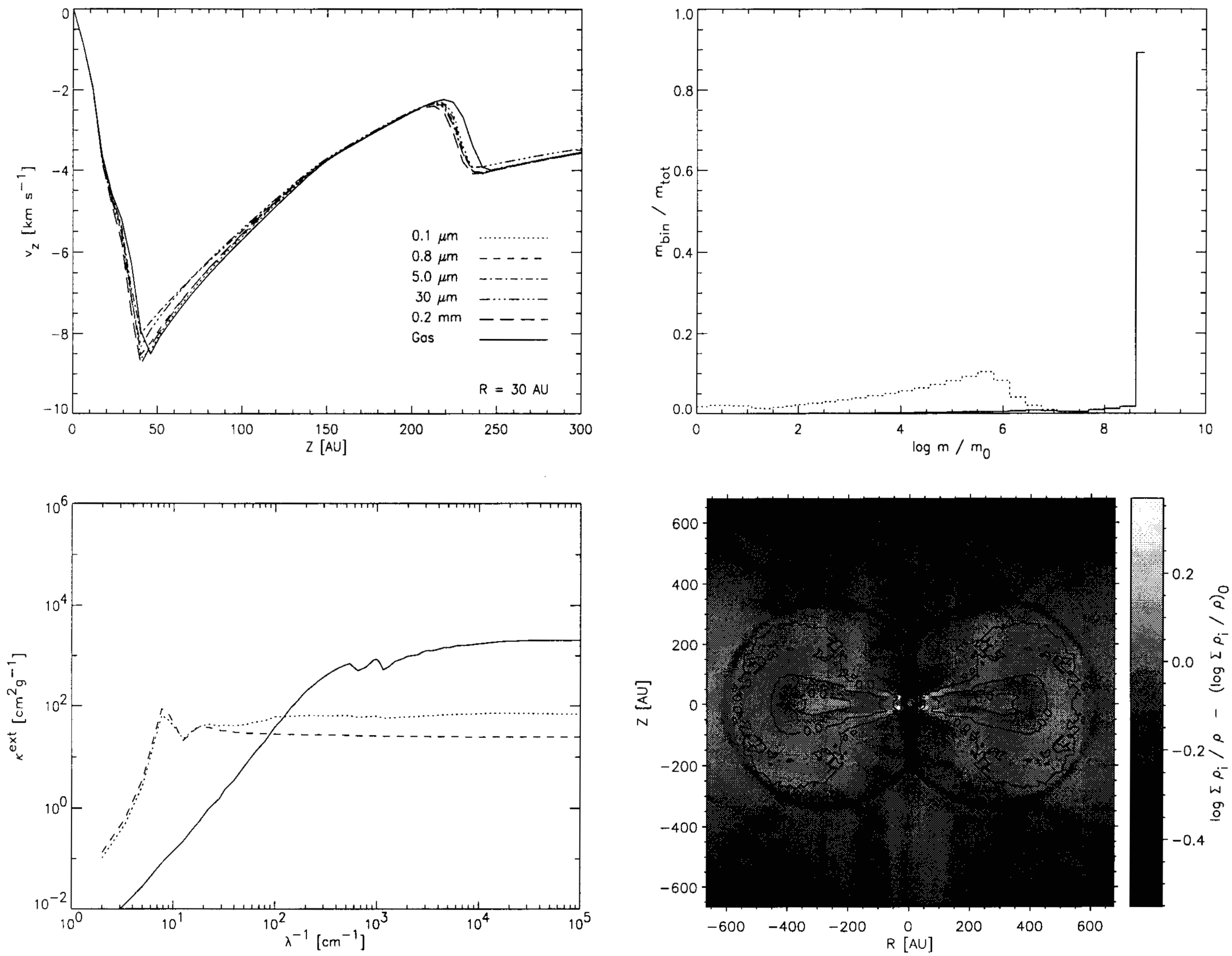
Effects of dust shattering in the inner accretion shock of a $10\,M_\odot$ model with BPCA–grains.

Dust evolution in protostellar accretion disks



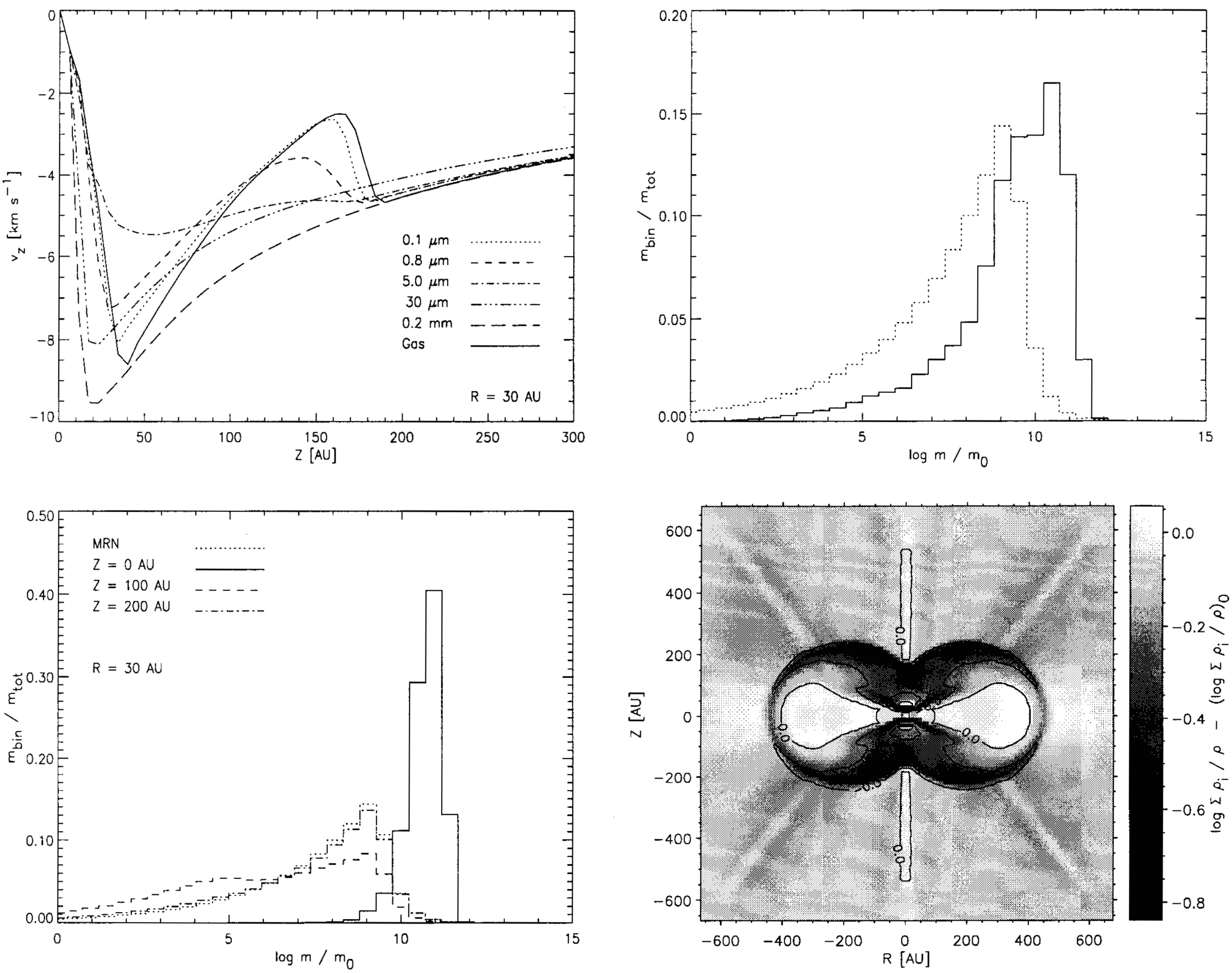
Density and velocity of the gas component of a collapsing, slowly rotating 3 $M_\odot$ dusty cloud at selected times: 0 yr (*u.l.*), 5100 yr (*u.r.*), 10300 yr (*l.l.*), 11400 yr (*l.r.*)

Fractal BCCA Grains at 12600 yr (3 $M_\odot$)

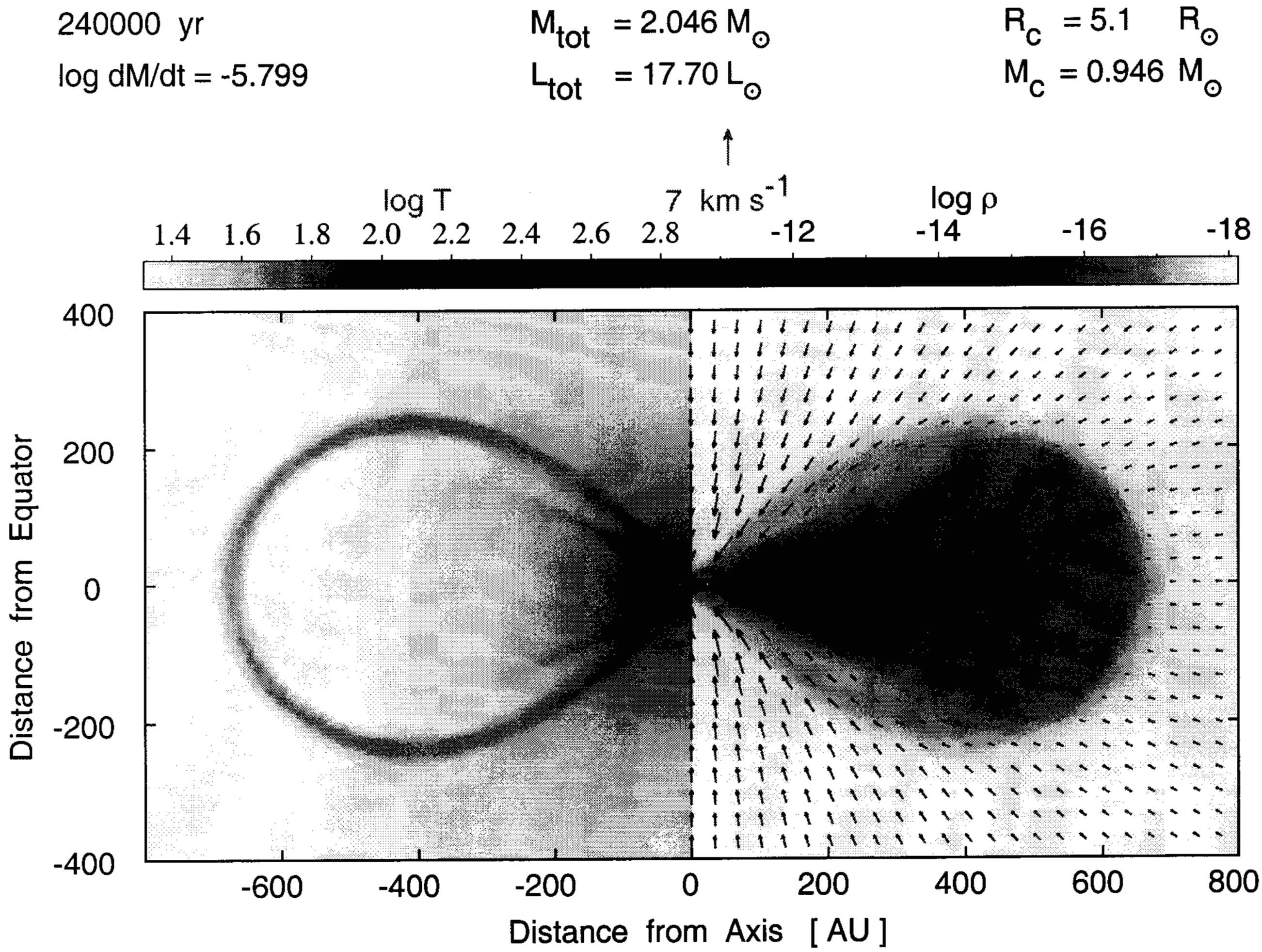


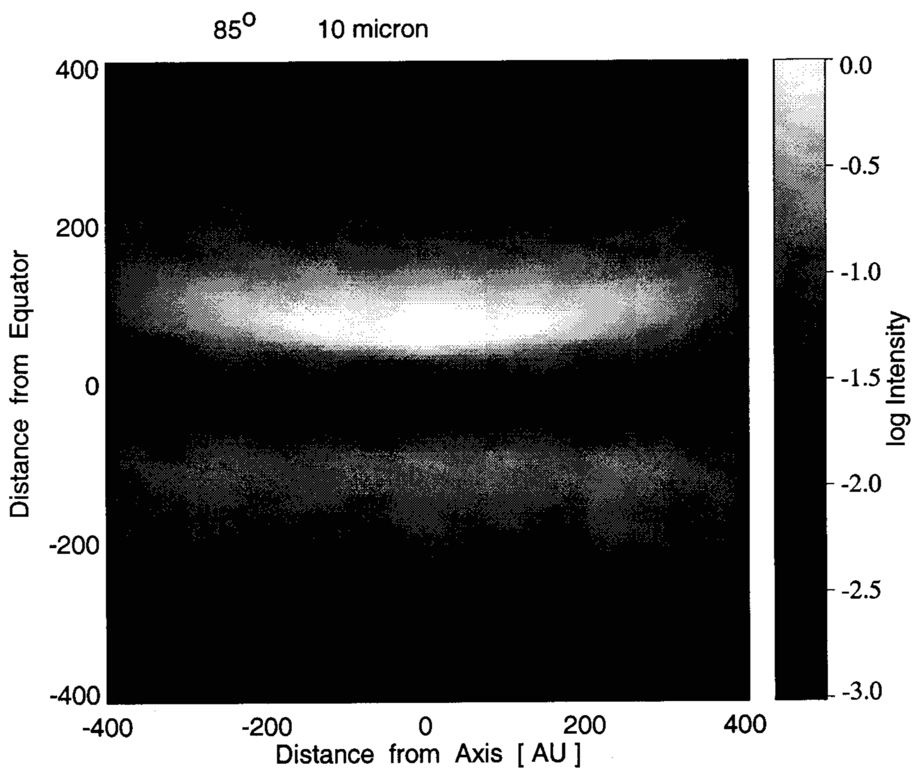
u.l.: Velocities of selected grains through the accretion shock at $R = 30$ AU. **u.r.**: Evolved total dust mass spectrum (*solid line*) and initial MRN distribution (*dotted line*). **l.l.**: Specific extinction coefficient at selected positions in the equatorial plane ($Z = 0\,$AU) at $R = 30\,$AU (*dashed line*) and $R = 300\,$AU (*dotted line*). For comparison the extinction coefficient of MRN dust is displayed as a solid line. **l.r.**: Dust to gas mass ratio.

Compact Spherical Grains at 11400 yr (3 $M_\odot$)



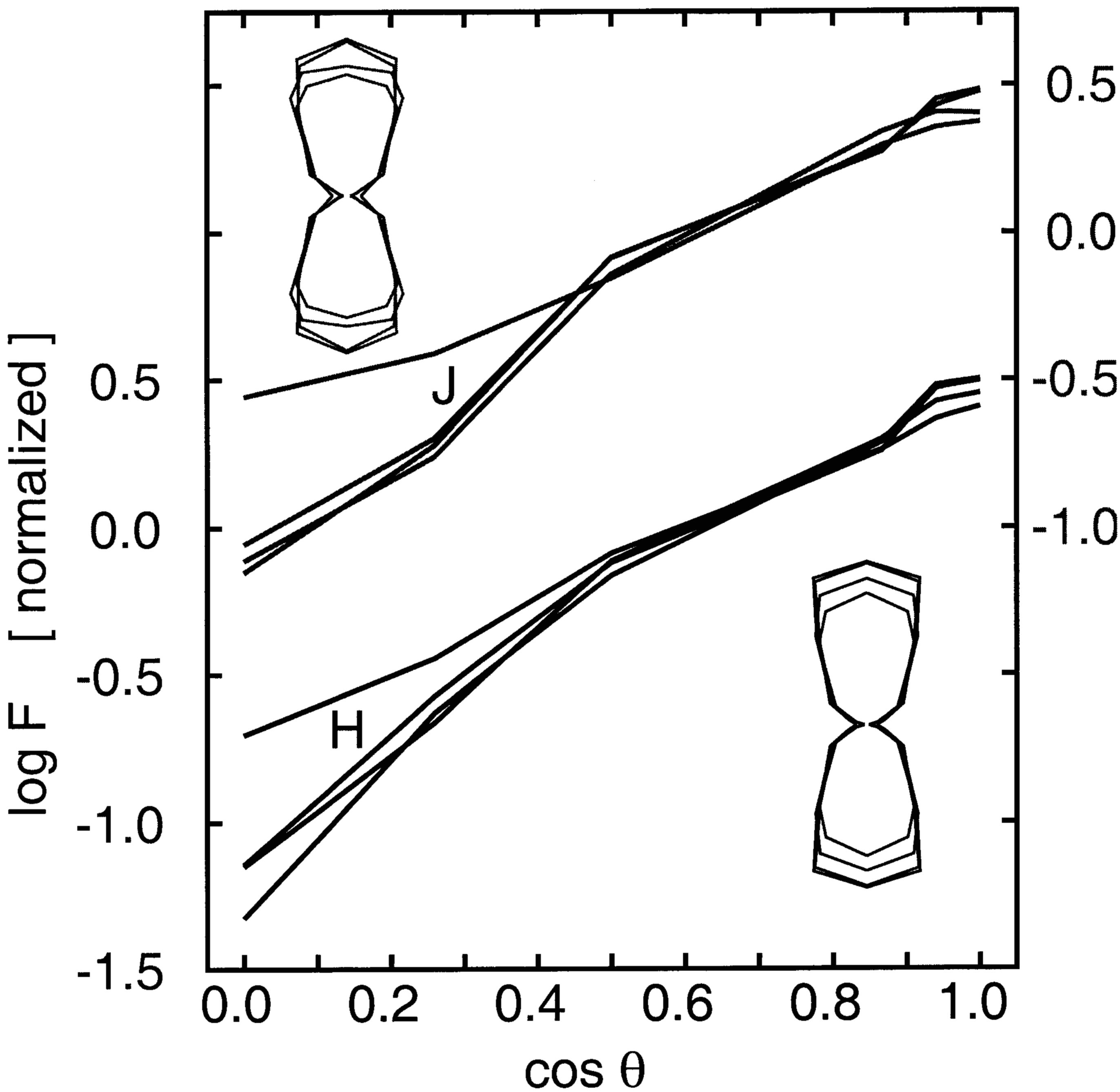
u.l.: Velocities of selected grains through the accretion shock at R = 30 AU. **u.r.**: Evolved total dust mass spectrum (*solid line*) and initial MRN distribution (*dotted line*). **l.l.**: Grain mass spectrum at selected positions along $R = 30$ AU. **l.r.**: Dust to gas mass ratio.


240000 yr
log dM/dt = -5.799
M_tot = 2.046 M_⊙
L_tot = 17.70 L_⊙
R_c = 5.1 R_⊙
M_c = 0.946 M_⊙
log T
7 km s^-1
log ρ
1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8
-12 -14 -16 -18
Distance from Equator
Distance from Axis [AU]
400 200 0 -200 -400
-600 -400 -200 0 200 400 600 800

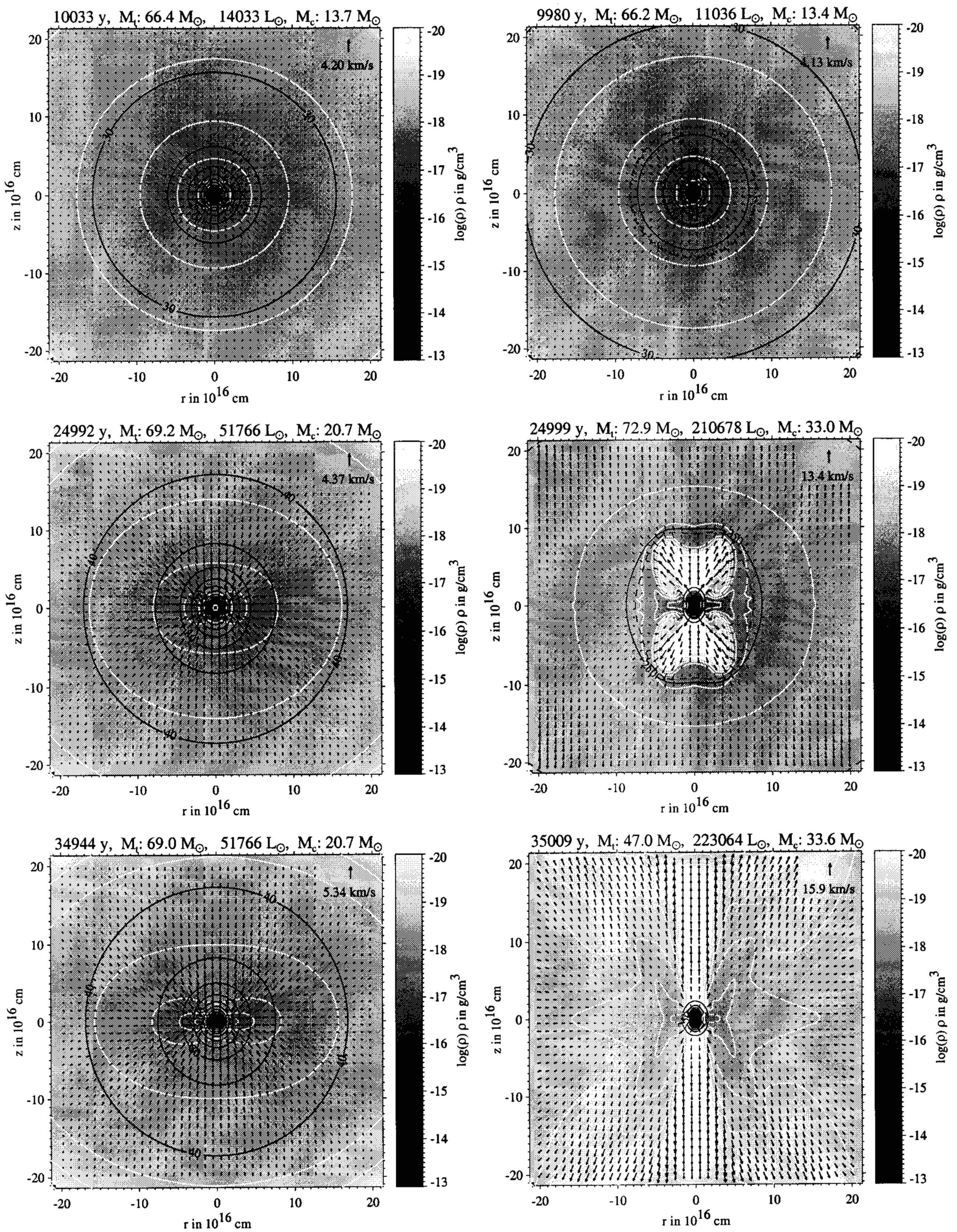

85°
10 micron
Distance from Equator
Distance from Axis [AU]
log Intensity
400 200 0 -200 -400
-400 -200 0 200 400
0.0 -0.5 -1.0 -1.5 -2.0 -2.5 -3.0

THE FLASHLIGHT EFFECT

(Yorke & Bodenheimer, 1999, ApJ, 525, 330)



Dependence of bolometric flux on viewing angle for cases H (2 $M_\odot$) and J (1 $M_\odot$). The value of $\log F = 0$ corresponds to the mean flux. The flattest curves in each set correspond to the earliest times: H (110,000 yr, 250,000 yr, 400,000 yr, 600,000 yr); J (45,000 yr, 120,000 yr, 191,000 yr, 213,000 yr)



Comparison between calculations using grey radiation transfer (left) and frequency dependent radiation transfer (right).

CONCLUSIONS

- Massive stars can be formed by accretion, but some grain preprocessing is necessary
- Disks will play an important role for allowing material to accrete onto the central star
- Massive stars photoionize close-by disks, producing UCHIIs
- The accretion and disk destruction processes operate on timescales of $\sim 10^5$ yr